AN APERTURE-COUPLED PATCH ANTENNA DESIGN FOR IMPROVED IMPEDANCE BANDWIDTH

William O. Coburn*, Steven D. Keller, Chad E. Patterson and Russell Harris
U.S. Army Research Laboratory
Adelphi, MD 20783

ABSTRACT

The Method of Moments, implemented in 2.5-D with the multilayer Green's Function, or implemented as a fully 3-D solution of Maxwell's equations, is a popular method for microwave antenna simulations. Commercial software was used to simulate two different designs for a single aperture-coupled patch antenna element. The simulation results are compared with experimental data measured for antenna prototypes having substrate and ground plane dimensions 4-in x 4-in. For *C*-Band applications (4.4 – 5 GHz) a conventional patch antenna solution, with stub-terminated microstrip feed and slotted ground plane, would not cover the entire band. A different design, incorporating thicker substrate layers and a bottom ground plane for unidirectional radiation, was modeled in 2.5-D with encouraging results. The design had improved bandwidth and was fabricated even though the simulations results were known to be approximate. The concern for the microstrip feed structure is the frequency variation of the propagation velocity and the presence of higher order waveguide modes that are not incorporated in the simulation but serve to limit the measured bandwidth. We compare the calculated and measured antenna performance and show that specialized software is often sufficient for the design of conventional aperture-coupled patch antennas but can be misleading for thick substrates.

1. INTRODUCTION

Communications systems will be vital to Future Combat Systems ability to use speed and information to dominate the modern battlefield. Point of Presence vehicles will be the Future Communication Systems platforms where key metrics for potential antenna solutions are size/weight and affordability. Patch antennas are a popular choice for microwave electronically scanned array applications. They offer low-profile, light-weight and low-cost solutions that can be readily integrated into microwave circuits. Their disadvantage is narrow impedance bandwidth (BW) where probe fed or proximity coupled patch antenna designs are typically limited to ~5% BW. An aperture-coupled patch antenna can have improved BW and we have used slot-coupled patches with stub-terminated microstrip feed line to obtain BW ~15%.

The Method of Moments, implemented in 2.5-D with the multilayer Green's Function, or implemented as a fully 3-D solution of Maxwell's equations, is a popular method for microwave antenna simulations. Commercial software was used to simulate two different designs for a single aperture-coupled patch antenna element. We use EMPiCASSO (EMP) from EMAG Technologies, Inc. (www.emagtech.com) to design such antennas, many of which have been fabricated and measured with excellent results. A different design with dipole-terminated microstrip feed line and thick substrate was simulated and optimized for broadband performance using EMP. For analysis we use FEKO from EM Software & Systems (www.feko.info) a fully 3-D implementation of the MoM in which the multilayer Greens Function can also be used for a 2.5-D model of semi-infinite substrates. Here we present the calculated and measured antenna characteristics for this new design compared to a conventional aperture coupled patch with microstrip feed line. For *C*-Band applications (4.4 – 5 GHz) a conventional patch antenna solution, with stub-terminated microstrip feed and slotted ground plane would not cover the entire band. A different approach incorporating thicker substrate layers and a bottom ground plane for unidirectional radiation was designed in 2.5-D with encouraging results. The design had circular polarization and improved BW and was fabricated even though the simulation results were known to be approximate. The concern for the microstrip feed structure is the frequency variation of the propagation velocity and the presence of higher order waveguide modes that are not incorporated in the simulation but serve to limit the measured BW. The bottom substrate has a high relative permittivity (ε_r = 6) and thickness similar to what would be encountered when embedding this antenna into composite structures.

For the conventional design the patch is over a slotted ground plane which is a 2.5-D model in EMP but is modeled as a finite size conducting patch in FEKO. These simulation results are compared with experimental data measured for antenna prototypes having substrate and ground plane dimensions 4-in x 4-in. The feed line extends to the edge of the substrate where a coaxial connector is installed between the feed and ground plane. The results are used to compare and contrast the use of EMP and FEKO for the design and analysis of an aperture-coupled patch antenna. For the thick substrate

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design with both EMP and FEKO we use 2.5-D models of the substrate layers and bottom ground plane but the slotted patch has a finite size.

2. EMPICASSO SIMULATIONS

A *C*-band patch antenna was designed as a 2.5-D model in EMP to operate with a resonant frequency between 4.4 and 5 GHz. Since the patch antenna is inherently a narrowband structure, it was not expected to cover this entire band, so the design focused on a center frequency, f_c = 4.6 GHz corresponding to a free-space wavelength, λ_0 = 2.57-in. The goal in the antenna design was maximize the -10dB return loss BW. The final antenna design is shown in Figure 1 with the detailed dimensions and substrate layer properties listed in Table 1 but the slotted ground is modeled as semi-infinite. The relative dielectric constant of the substrate layers were set to ε_r = 2.33 to represent Rogers RT/duroid® 5780 low-loss dielectric (www.rogerscorporation.com). Then the effective wavelength in the substrate, $\lambda_{eff} = \lambda_0/\sqrt{\varepsilon_r}$ = 1.68-in. is used for mesh refinement in the aperture and on the microstrip feed with 80 samples/λ_{eff} rather than the default 30 samples. The 5780 substrate is 2 oz. copper clad amounting to about 1 mil copper thickness and the different layers are bonded with 3M Scotch® adhesive transfer tape (www.3m.com).

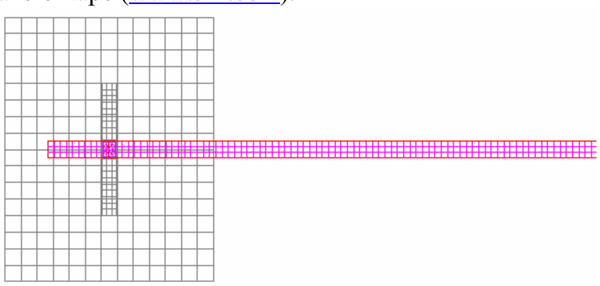


Figure 1. An aperture-coupled patch antenna design in EMPiCASSO showing the mesh refinement.

Table 1. Thin-Substrate Patch Antenna Parameters.

Layer Description	**Dimensions and Substrate Thickness (mil)**
Patch (Copper)	680 x 860 mil patch
Upper Substrate (RT/duroid 5780)	4000 x 4000 mil, 125 mil thickness
Slotted Ground Plane (Copper)	4000 x 4000 mil with 50 x 430 mil slot
Lower Substrate (RT/duroid 5780)	4000 x 4000 mil, 20 mil thickness
Microstrip Feed Line (Copper)	55 mil width, 2200 mil total length extending 200 mil past slot center

The adhesive layer is neglected in the simulations and the conductor surfaces are approximated as a zero thickness Perfect Electric Conductor (PEC). The EMP simulations provide directivity and S-parameters where the gain is assumed equivalent to directivity since the antenna losses are small. We use the input reflection coefficient to obtain the approximate realized gain for comparison to measurements. The design involved a number of modeling approximations, including an infinite slotted ground plane and infinite substrate, with a feed line trace that EMP automatically extends to ~2λ_{eff} at each excitation frequency. A port excitation was placed along this feedline roughly at the center and simulated using the MoM technique in EMP. A convergence study showed that the default mesh size was sufficient except for the slot and microstrip feed line where mesh refinement is needed to improve accuracy. The simulation took ~30 seconds per frequency or about 10 minutes to complete a 21 point sweep from 4.4 to 4.8 GHz.

A similar design, but incorporating another thick substrate layer and bottom ground plane, was also modeled using EMP. The dyadic Green's function contour integration should be able to capture poles corresponding to surface waves except in the case of very thin layers (λ_{eff}/100) where convergence can be an issue. But for a 2.5-D model there will be no contributions to the radiation pattern from the substrate edges which can be important for thick substrate design approaches. The mesh discretization is shown in Figure 2 with the layer properties summarized in Table 2 where the slotted patch is modeled with finite size. The 2.5-D simulation results are compared to the experimental data for a prototype antenna fabricated on a 4-in square substrate.

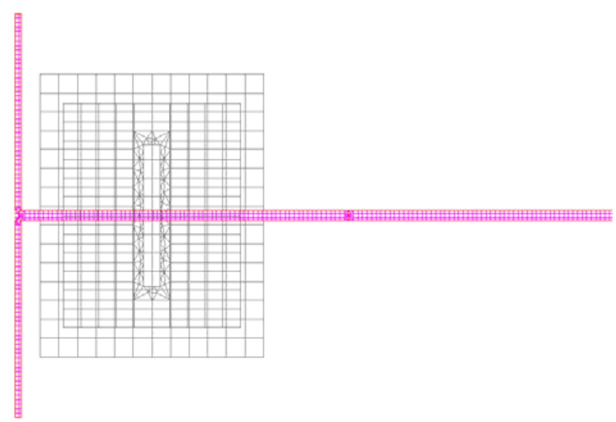


Figure 2. Thick-substrate patch antenna design in EMPiCASSO showing the mesh refinement.

Table 2. Thick-Substrate Patch Antenna Parameters.

Layer Description	**Dimensions and Substrate Thickness (mil)**
Patch (Copper)	540 x 680 mil patch
Upper Substrate (RT/duroid 5780)	4000 x 4000 mil, 312 mil thickness
Slotted Patch (Copper)	680 x 860 mil with 50 x 430 mil slot
Middle Substrate (RT/duroid 5780)	4000 x 4000 mil, 20 mil thickness
Microstrip Feed Line (Copper)	30 mil width, 2400 mil total length extending 400 mil past slot center
Dipole Termination	15 mil width, 1230 mil total length
Copper Clad Bottom Substrate (Composite, $\varepsilon_r = 6$)	4000 x 4000 mil, 200 mil thickness

3. FEKO SIMULATIONS

The aperture-coupled patch antennas that were designed and optimized in EMP were then analyzed using FEKO. The Feko model for the conventional design thin-substrate patch antenna is shown in Figure 3, where the ground plane dimensions were set to the as-fabricated antenna dimensions, 4000 x 4000 mil, and the feed line extends 2000 mil from the aperture center to the ground plane edge. The multi-layer Green's Function was used for a semi-infinite model of the substrates with this finite size ground plane. We applied a voltage excitation to a wire segment connecting the end of the feed line to ground rather than a lumped port excitation as in EMP. Symmetry is used to reduce the Feko memory requirements and mesh refinement is required for improved accuracy as shown in Figure 3.

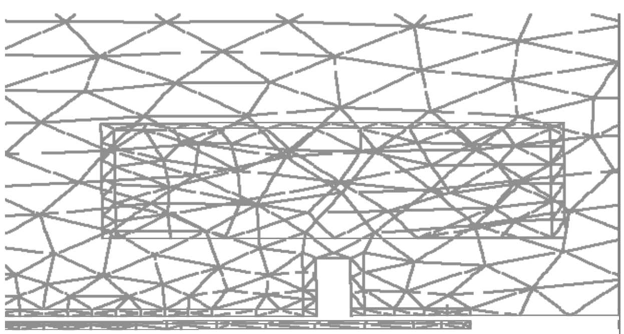


Figure 3. Aperture-coupled patch antenna model in FEKO using symmetry with mesh refinement.

We ran a number of different simulations using this model, with various refinement of the triangular mesh. With a smaller mesh size we have more elements, potentially offering a more accurate solution at the cost of increased simulation runtime and increased system memory usage. The model required mesh refinement in the microstrip feed and around the edges of the patch and the slot in the ground plane. Notice that the ground plane also includes a finer mesh above the microstrip feed, as suggested by the FEKO development team, for improved accuracy when using microstrip above a finite size ground plane. FEKO provides directivity and realized gain according to the impedance mismatch. The simulations for a 21 point frequency sweep (4.4 – 4.8 GHz) require ~ 3 hours significantly more time than EMP.

The thick substrate design is shown in Figure 4 where we use a similar mesh refinement of the microstrip, patch and slot. The multi-layer Green's Function was used for the substrates and bottom ground plane corresponding to a 2.5-D model similar to EMP. In this model we use a microstrip excitation since there is a semi-infinite bottom ground plane. This requires an additional vertical strip connected to ground (not shown), where we apply an edge excitation rather than a wire-feed as was used in the thin-substrate design. We also use a finite size ground plane with the semi-infinite substrates with little difference in results. A fully 3-D model can also be constructed for analysis but quickly overwhelms the computational resources of a conventional PC. The simulation results are used for comparison with the EMP results and with experimental data measured for the antenna prototypes.

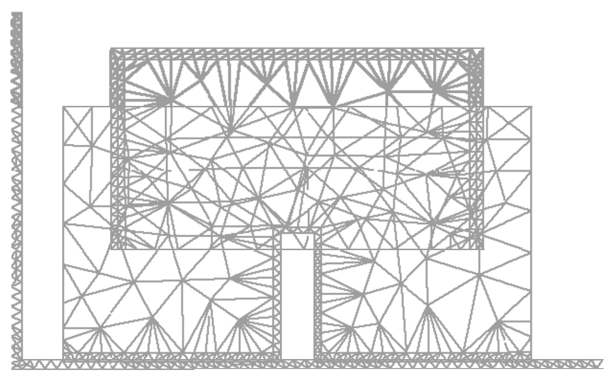


Figure 4. Thick-substrate patch antenna 2.5-D model in FEKO using symmetry with mesh refinement.

4. EXPERIMENTAL DATA

A prototype of the conventional aperture-coupled patch antenna design was constructed using an onsite router on RT/duroid substrates, which are then adhesive bonded. The thick-substrate design was fabricated by Modular Components National (www.modularcomp.com) to our specifications using adhesive bonding between layers. The 5780 has a relative dielectric constant of approximately $\varepsilon_r = 2.33$ as measured with the split cavity method by Damaskos, Inc. (www.damaskosinc.com). We measured the return loss data using a network analyzer

and the gain and radiation patterns were measured in an onsite tapered anechoic chamber.

4.1 Network Analyzer Measurements

The dielectric and conductor losses are treated as independent loss mechanisms but for typical materials these losses are negligible. The impedance mismatch to the antenna determines the input reflection coefficient, Γ, or in terms of *S*-parameters, $\Gamma = S_{11}$. Performance is often characterized by the return loss, RL = $20\log(|\Gamma|)$, or alternatively by the input voltage standing wave ratio, VSWR = $(1 + |\Gamma|)/(1 - |\Gamma|)$. Typical *C*-Band specifications are VSWR < 1.6 over the range 4.4 – 5 GHz corresponding to RL < −13 dB. The measured data was obtained with a Wiltron 37269A vector network analyzer (VNA) calibrated using the Wiltron K-Cal Kit Model 3652 (www.anritsu.com). When care is taken to make consistent connections, the measurement repeatability is on the order of ±0.05 dB, which is more than sufficient for research purposes.

4.2 Antenna Pattern Measurements

We conducted the radiation pattern and gain measurements using a *C*-band Standard Gain Horn (SGH) antenna as the system transmitter and setting up the prototype patch antenna on a non-metallic rotating positioner to serve as the receiver as shown in Figure 5.

Figure 5. Radiation pattern measurement setup in the anechoic chamber.

We conducted the antenna measurements in an absorber-lined tapered anechoic chamber (Weiss, et. al., 1995). The length of this chamber is about 50 ft with the actual distance between transmit and receive antennas being 45.3 ft. A diagram for the antenna pattern measurements is shown in Figure 6 using the substitution technique with Narda SGH antennas (www.nardamicrowave.com). The receiver is phase-locked to the transmitter with computer controlled data acquisition and rotation. The pattern measurements are calibrated according to power meter data versus frequency at the test antenna boresight position. Magnitude and phase data is collected every 1.02° with an accuracy of 0.1°, although this does not account for position error in placement of the antenna on the rotator.

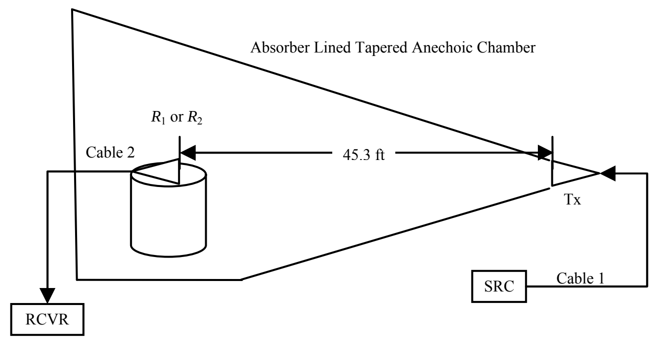


Figure 6. Schematic diagram of antenna measurements using the substitution method.

Two identical Narda SGH antennas, having known gain relative to an isotropic radiator (dBi) over the rated bandwidth, are used as the reference antennas. The receive SGH is then replaced with the antenna under test. The exact position of the reference and test antennas on the pylon is a source of uncertainty that is minimized but not completely eliminated. The receive pattern for the radiating antenna is measured versus angle with the experimental error estimated from the repeatability of the data after repositioning the antenna. The repeatability error can be minimized with careful procedures and placement of the antenna on the rotating pylon but it is not negligible, typically ±0.25 dB.

5. RESULTS

After the prototype return loss and radiation pattern data were measured, it was then processed and compared with the results from the EMP and FEKO simulations. The conventional design patch antenna S_{11} comparison is shown in Figure 7 for measurements in the range 4.4 – 4.8 GHz. The EMP simulation results are very close to measurements and this software has been used successfully many times for optimizing a design so that the resulting performance meets the antenna specifications. The S_{11} results are in reasonable

agreement with EMP obtaining a somewhat larger -10 dB return loss or impedance BW (330 MHz) than measured (300 MHz). The EMP simulation obtained a center frequency of ~4.580 GHz being very close to the measured value of ~4.583 GHz. FEKO also obtains ~300 MHz impedance BW, but a resonant frequency of 4.572 GHz with a minimum return loss consistent with measurements. Except for this lower resonance, FEKO could also be used to design such patch antennas but requires much longer run times compared to EMP. We also used Ansoft's (www.ansoft.com) High Frequency Structure Simulator (HFSS) finite element code to model this antenna with results similar to FEKO (Keller, et. al., Army Research Laboratory, in-press). For this antenna the difference between EMP and FEKO (or HFSS) should be small and would normally be neglected.

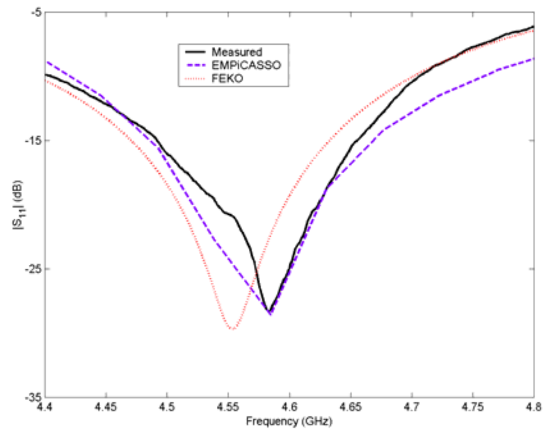


Figure 7. S_{11} comparison for a thin-substrate aperture-coupled *C*-band patch antenna.

The thick-substrate patch antenna S_{11} comparison is shown in Figure 8 for measurements in the range 4 – 6 GHz. The EMP simulation results compare poorly to measurements possibly because this software is inappropriate for designs combining very thin substrates with much thicker layers. The Feko results are in reasonable agreement predicting the dominant resonant frequencies of approximately 4.1, 4.9 and 5.9 GHz. HFSS produced results similar to EMP indicating a viable design so that FEKO was the preferred method, even though it was a 2.5-D model compared to a 3-D model in HFSS. It appears that this design incorporating thick substrates and multiple resonances would not be an effective solution to increase the impedance BW of patch antennas. But a 2.5-D model in EMP (and 3-D model in HFSS) predicted reasonable performance, so the design was optimized in EMP and fabricated based entirely on simulation results. Of course, we expected the performance to be more limited than these model results predicted, but we desired experimental confirmation. Based on the 2.5-D FEKO simulations, this design would not have been pursued as having improved impedance BW compared to a more conventional design approach.

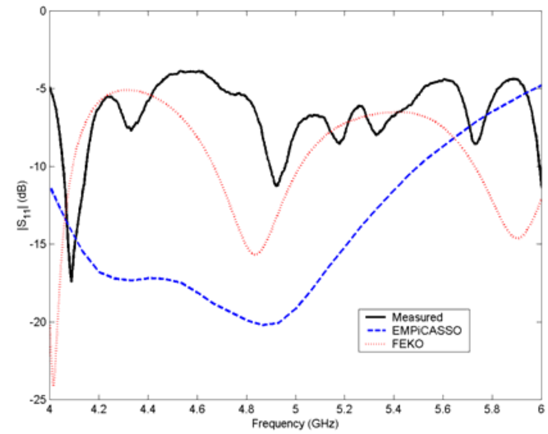


Figure 8. S_{11} comparison for a thick-substrate aperture-coupled *C*-band patch antenna.

The measured radiation pattern data are compared to simulated radiation patterns from EMP and FEKO. The measured data corresponds to realized gain, G_r, but only directivity is available from the EMP simulations. Since the antenna losses are small, the calculated directivity should be nearly the same as the gain whereas the realized gain also includes impedance mismatch losses. The directivity is assumed to be equivalent to gain, G_0, then it can be converted to G_r based on the calculated reflection coefficient versus frequency, $G_r = G_0(1 - |\Gamma|^2)$. The measured E-plane G_r is compared to the EMP and FEKO gain and realized gain in Figure 9 for the conventional patch antenna design. The comparison is for peak gain corresponding to boresight gain for EMP but at $\theta \sim 30°$ for the measured and FEKO results. The measured G_r near the resonant frequency of 4.58 GHz is about 8 dBi, with EMP being in fair agreement at 7.4 dBi, but the FEKO result is lower than measured being only 6.7 dBi. The EMP realized gain is within about 1 dB of the measurements whereas the FEKO realized gain is 1 – 2 dB less than EMP.

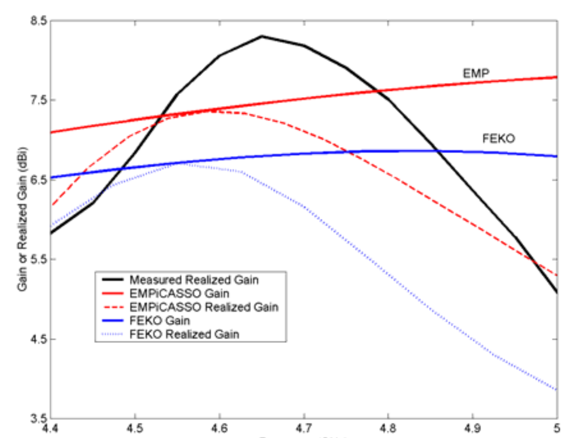


Figure 9. Measured E-plane realized gain compared to EMP and FEKO for an aperture-coupled patch antenna.

The measured and simulated radiation patterns for the thin-substrate antenna at 4.55 GHz are compared in Figure 10 for the E-plane pattern and in Figure 11 for the H-plane pattern as a function of elevation angle at fixed azimuth. The FEKO simulation results seemed to match the pattern shape of the measured data better than the EMP simulation, but seemed to be less accurate for the antenna realized gain. EMP had a more idealized pattern and did not predict the reduced gain on boresight observed in the E-plane pattern in both the measured and FEKO results. The EMP simulation results tended to match the main lobe reasonably well, but did not accurately predict the variations in the backplane radiation. The EMP 2.5-D model has backplane radiation owing to leakage through the slotted ground plane rather than the effects of a finite-size ground, so these simulation results are as expected. FEKO has back lobes associated with diffraction effects from the finite ground. However, it does not accurately account for backward radiation through the slot. FEKO obtains similar back lobes in the E-plane pattern as measured, but the H-plane has smaller back lobes. The measured backplane pattern has about the same peak level in both cut planes. Both simulation methods underestimate the peak backplane radiation level especially for the H-plane pattern.

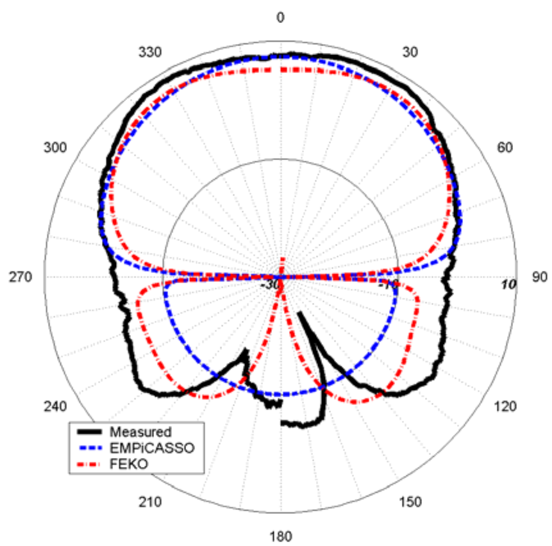


Figure 10. Aperture-coupled patch antenna E-Plane radiation pattern comparison at 4.55 GHz.

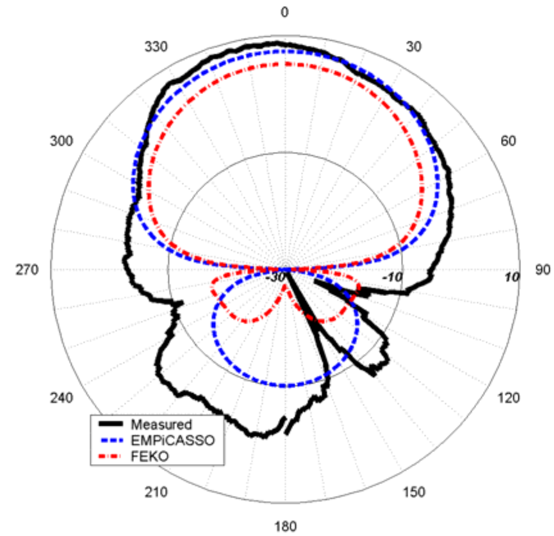


Figure 11. Aperture-coupled patch antenna H-Plane radiation pattern comparison at 4.55 GHz.

The measured and simulated radiation patterns for the thick-substrate antenna at 4.9 GHz are compared in Figure 12 for the E-plane pattern and in Figure 13 for the H-plane pattern as a function of elevation angle at fixed azimuth. Only a few measurements have been conducted on this antenna to date, so only limited pattern data were available at this time for the vertical and horizontal components in two cut planes. We compare all the patterns normalized to their peak amplitude for clarity in comparing pattern variations. The simulation results did not match the pattern shape of the measured data and EMP greatly overestimated the antenna directivity. The simulation results correspond to an infinite bottom ground plane, so there is no backplane radiation. With FEKO we also used a finite size bottom ground plane with only minor differences but longer run times since this surface now has to be meshed increasing the number of triangles. There were only minor differences in S_{11} and very little backplane radiation so a 2.5-D model of all substrates and the bottom ground plane were used for analysis. The radiation is circularly polarized but was only measured in the principal planes corresponding to vertical (E-plane) and horizontal (H-plane) co- and cross-polarized components.

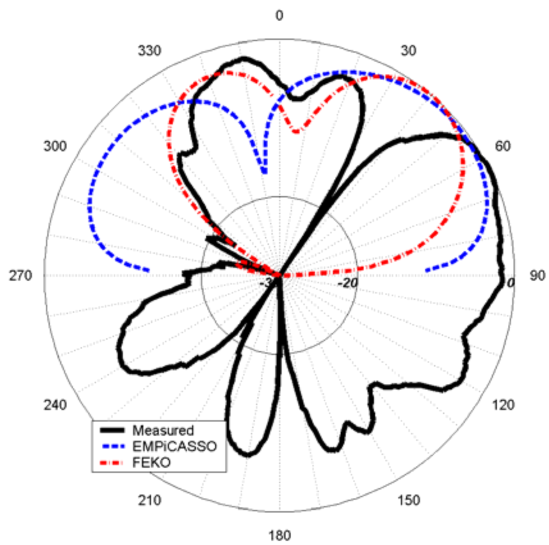


Figure 12. Thick-substrate aperture-coupled patch antenna E-Plane radiation pattern comparison at 4.9 GHz.

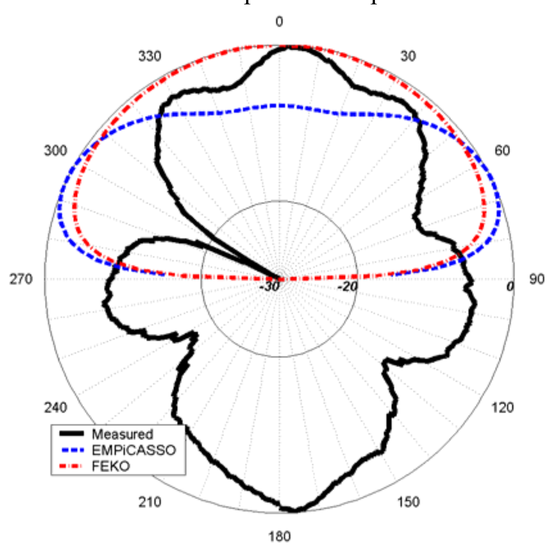


Figure 13. Thick-substrate aperture-coupled patch antenna H-Plane radiation pattern comparison at 4.9 GHz.

The EMP 2.5-D model predicted a reasonable boresight gain for this antenna as shown in Figure 14, while FEKO is at least 15 dB lower. The EMP results approach the measured gain at some frequencies whereas FEKO predicts very poor antenna efficiency at all frequencies. The calculated E-plane gain is in poor agreement with measurements and also between the two simulation methods. The H-plane pattern is more symmetric as expected with the simulation results being in fair agreement but the measurements indicate a more complicated radiation pattern. In the H-plane pattern the cross-polarized component has the expected symmetry but EMP predicts that this component is about 10 dB larger than measured or predicted by FEKO as shown in Figure 15.

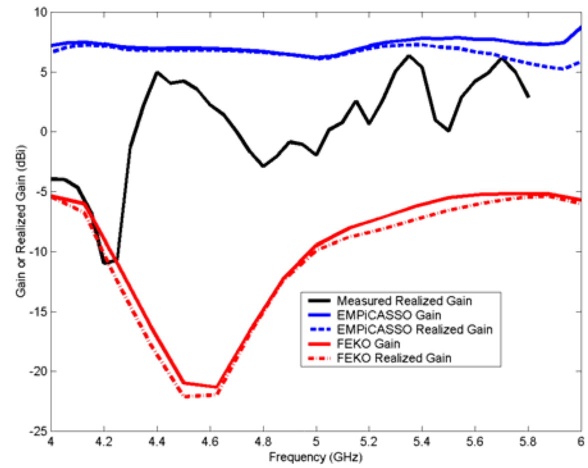


Figure 14. Thick-substrate aperture-coupled patch antenna boresight gain comparison as a function of frequency.

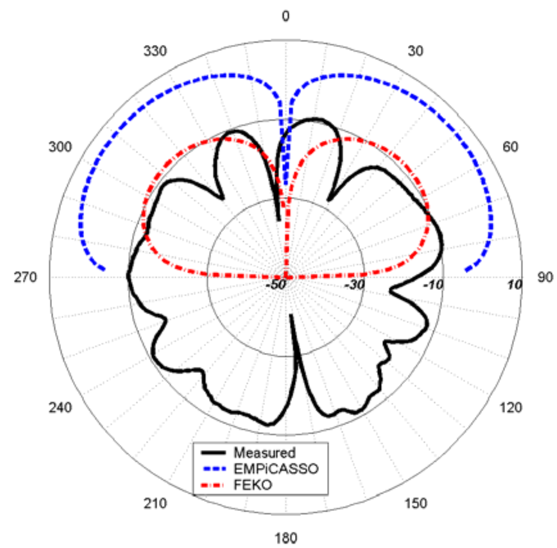
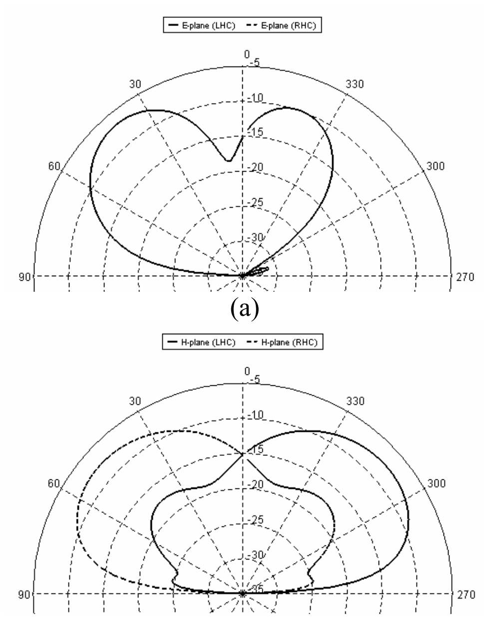


Figure 15. Thick-substrate aperture-coupled patch antenna H-plane gain comparison for cross-polarized component.

The radiation is actually circularly polarized as can be seen in the FEKO results for the E-plane and H-plane patterns shown in Figure 16 (a) and (b), respectively. The E-plane left-hand circular (LHC) and right-hand circular (RHC) polarizations are equivalent whereas they are anti-symmetric in the H-plane. FEKO predicted a poorly radiating antenna and complicated input impedance similar to measured. The antenna actually radiates from its edges leading to a complicated pattern with large back lobe levels. Neither simulation method using the multi-layer Green's function will be able to reproduce these patterns. A fully 3-D model with FEKO is still under investigation. Even if better accuracy could be obtained with 3-D models, the simulations would be highly inefficient compared to the speed of EMP.



(a)

(b)

Figure 15. FEKO thick-substrate aperture-coupled patch antenna (a) E-plane pattern and (b) H-plane pattern.

CONCLUSIONS

The accuracy and efficiency of the *EMAG* EMPiCASSO and FEKO software packages were compared with experimental results for two aperture-coupled *C*-band patch antenna geometries. Both methods are possible for conventional thin-substrate patch antenna designs. But since EMP is faster it would be the preferred method unless finite size substrates and ground plane are required. For the thin-substrate design, the difference between finite size slotted ground and a 2.5-D model is not large and primarily affects the backplane radiation pattern. EMP has reasonable accuracy for simulating front plane radiation, while a finite ground plane FEKO model may be more useful for simulating back plane radiation. However, in this study neither approach was sufficient for accurately predicting the backplane radiation amplitude or pattern for the conventional thin-substrate patch antenna.

The EMP software is less accurate for the thick-substrate design since it predicted reasonable S-parameter and radiation pattern results with gain on the same order as the conventional patch antenna design. The measured data indicate that the thick-substrate approach is a poor design and FEKO obtained similar results as measured for the input impedance but not the realized gain. It is interesting to note that the HFSS 3-D model results were more similar to EMP so that FEKO obtained better results. FEKO provides an accurate solution for the thin-substrate aperture-coupled patch antenna. However, EMP would provide more accurate and more efficient S-parameter solutions running many times faster than FEKO (or HFSS). For radiation patterns, the results above suggest that 2.5-D models will not result in an accurate prediction of the true radiation pattern for thick-substrate designs.

For thin-substrate patch antenna designs, the software explored in this paper offers advantages and disadvantages depending on what parameters must be simulated. For the antenna input impedance, EMP will offer the most accurate and efficient solution subject to its inherent approximations. For gain data, neither program will offer fully accurate results, but EMP appears to be more accurate compared to the measured data. It is expected that a FEKO (or HFSS) 3-D model would provide more accurate results for thick-substrates and would be useful for exploring the effects of a finite ground plane but this is still under investigation. For radiation pattern data EMP provides a sufficiently accurate depiction of the front plane pattern with an idealized back plane pattern. FEKO may be useful for finite size planar antennas, but care must be taken to obtain a sufficiently refined model and a full convergence study would be required. With FEKO such an effort may not be justified for obtaining better accuracy compared to a 2.5-D model such as EMP, which is reasonable accurate, fast, and has been successfully used for the design of aperture-coupled patch antenna arrays.

We have shown that EMP fails in some cases so that FEKO is an alternative way to analyze such structures. We showed that a 2.5-D model in FEKO produced reasonably accurate input impedance but idealized patterns compared to measurements. For a 3-D model, a finite size substrate and ground plane must be included with suitable mesh refinement leading to a large problem requiring significant runtimes. Our thick-substrate antenna as fabricated has a complicated circularly-polarized radiation pattern and significant back plane radiation even though there is a bottom ground plane. This implies that the finite size substrate layers must be accurately modeled in order to predict the radiation pattern. Additional modeling and measurements will be required to adequately decide which code will be most appropriate to analyze thick-substrate antennas such as may be required to integrate patch antennas into layered composite structures.

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